

# Neutron star oscillations and QPOs during magnetar flares

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## Abstract

The high frequency oscillations discovered in the tails of giant flares from two magnetars are thought to be the first direct detections of seismic vibrations from neutron stars. The possibility of starquakes associated with the giant flares triggering global vibrations opens up the prospect of using seismology to study the interior structure and composition of neutron stars. This is a major breakthrough in the study of the nature of matter under conditions of extreme pressure. In this paper we provide an up to date summary of the observations and the theoretical framework, including a brief discussion of gravitational wave searches for the QPOs. We summarize the status of alternative non-seismic mechanisms, and give a critique of a recent paper by Levin that argued against seismic vibrations as a viable mechanism. We conclude with an overview of current results using the seismological technique that constrain parameters such as the equation of state and crust structure.

## *Key words:*

Magnetars, Neutron stars, Seismology

PACS: 26.60.+c, 97.10.Sj, 97.60.Jd

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## 1 Introduction

The Soft Gamma Repeaters are isolated compact objects that exhibit regular gamma-ray flaring activity. They are thought to be magnetars, neutron stars with external magnetic fields in excess of  $10^{14}$  G and internal fields that could be as high as  $10^{16}$  G (Duncan & Thompson, 1992; Thompson & Duncan, 1995). Decay of the field powers both regular small-scale flares and rare giant flares that are orders of magnitude more energetic. Three such events have been observed in the era of satellite-borne high energy detectors: in 1979 from SGR 0526-66 (Mazets et al., 1979), in 1998 from SGR 1900+14 (Hurley et al., 1999; Feroci et al., 1999), and in 2004 from SGR 1806-20 (Terasawa et al., 2005; Palmer et al., 2005; Hurley et al., 2005). The giant flares consist of a short hard flash (lasting less than a second), following by a softer decaying tail that persists for several hundred seconds. Pulsations with periods of several seconds become visible during the tail, revealing the spin period of the neutron star. They are due to a fireball of ejected plasma, trapped near the stellar surface by the strong magnetic field (Thompson & Duncan, 1995).

The giant flares are powered by catastrophic global reconfigurations of the magnetic field. However, the field is anchored to the charged particles in the neutron star crust. It had therefore long been suspected that giant flares might trigger starquakes (Flowers & Ruderman, 1977; Thompson & Duncan, 1995, 2001; Schwartz et al., 2005) that would be sufficiently energetic to excite global seismic vibrations (Duncan, 1998). The precise relationship between crust fracture and flare is not yet clear. In the model of Thompson & Duncan (1995) the field twists and puts the crust under strain, but crustal rigidity prevents movement and reconnection. Only when the crust reaches its breaking strain is a flare triggered. In the alternative model of Jones (2003) the crust deforms plastically as the field twists, and flares occur when the field reaches an instability point (Lyutikov, 2003). Even if the crust does not undergo brittle fracture, however, colossal and rapid reconfiguration of the field alone could be enough to drive global magneto-elastic vibrations.

Neutron stars can sustain many types of oscillation restored by various different forces. Early calculations for neutron star models with a fluid core and a solid crust indicated that the modes most likely to be excited by a magnetar crustquake were the torsional shear oscillations of the crust, with a fundamental frequency at  $\approx 30$  Hz (Schumaker & Thorne, 1983; McDermott, van Horn & Hansen, 1988; Strohmayer, 1991; Duncan, 1998). These oscillations are primarily horizontal (as opposed to radial) and are restored by the shear modulus in the crust. In what follows we use the quantum numbers  $l$  and  $m$  as the standard labels for angular harmonics, and the quantum number  $n$  to denote the number of nodes in the radial eigenfunction that describes the horizontal motion. The precise harmonics excited would depend on fracture properties (location,

geometry, speed), and subsequent coupling and damping processes. The means by which modes modulate the x-ray lightcurve will also be important: some modes may be excited but not detectable due to the way that they couple to the external field.

## 2 Observations

### 2.1 *Oscillations in the decaying tail*

On December 27th 2004, the most energetic giant flare ever recorded was detected from SGR 1806-20 (Terasawa et al., 2005; Palmer et al., 2005). Analysing data of the decaying tail from the *Rossi X-ray Timing Explorer* (RXTE) Proportional Counter Array (PCA), Israel et al. (2005) found a highly significant Quasi-Periodic Oscillation (QPO) at 92 Hz. The QPO was strongly rotational phase dependent, appearing for only part of the rotational cycle away from the main peak of the rotational pulse. Weaker features at 18 and 30 Hz were also found. The 30 Hz and 92 Hz QPOs were in line with the predictions of models for the fundamental torsional shear mode ( $n = 0, l = 2$ ) and one of the  $n = 0$  angular overtones. The 18 Hz QPO was rather too low in frequency to fit torsional shear mode models: Israel et al. (2005) suggested that it might instead be some kind of internal mode restored by the strong field.

Prompted by this discovery, Strohmayer & Watts (2005) analysed RXTE PCA data from the August 27th 1998 giant flare from SGR 1900+14. Although the data are not as high quality as for the SGR 1806-20 giant flare (there are data gaps due to the satellite configuration), we found a strong transient QPO at 84 Hz. Focusing on the rotational phase where the 84 Hz QPO was strongest, and folding multiple cycles from the whole tail of the flare, we found additional QPOs at 28, 54 and 155 Hz. The set of four QPOs could be fitted with a sequence of  $n = 0$  torsional shear modes of different angular harmonic number  $l$ , with the 28 Hz QPO as the fundamental.

So by September 2005 QPOs with similar frequencies and properties had been discovered in the decaying tails of giant flares from two different objects. The QPOs appeared to be transient, but because it was necessary to fold multiple cycles to detect most of the QPOs it was not clear when the oscillations were excited. However they were only seen clearly once the rotational pulsations were established, suggesting an association with the surface. In addition both the 92 Hz QPO for SGR 1806-20 and all of the SGR 1900+14 QPOs were strongly rotational phase dependent. This raised interesting questions. Was the transience and rotational phase dependence caused by material obscuring our view of the star (such as the rotating fireball)? And how did magnetic

field geometry affect mode patterns, survival of modes and their visibility?

For the SGR 1900+14 flare the RXTE PCA data are the only high time resolution data available for the tail. For the SGR 1806-20 flare, several other high time resolution instruments might have obtained useful data. The SWIFT Burst Alert Telescope (BAT) did record high time resolution data of the initial part of the flare, but unfortunately the time resolution dropped 20s into the flare, before the QPOs established themselves (Palmer et al., 2005). The *International Gamma-Ray Astrophysics Laboratory* (INTEGRAL) also caught the flare. However the time resolution of the lightcurve obtained using the anti-coincidence shield on the spectrometer was, at 50ms (Mereghetti et al., 2005), too low for our purposes, and the countrate on the higher time resolution Joint European X-ray Monitor (JEM-X) was too low to be useful (Brandt et al., 2005).

The only other spacecraft to get high time resolution data of the tail of the flare was the *Ramaty High Energy Solar Spectroscopic Imager* (RHESSI), which was fortuitously pointing almost directly at the flare. RHESSI is a segmented detector covering both the RXTE energy band and higher energies. When both front and rear segments are taken into account RHESSI recorded a higher countrate than RXTE. However, the rear segments were strongly affected by albedo flux due to reflection from the Earth, which complicated timing analysis. As such it was not possible to include events from the rear segments when searching for QPOs above 50 Hz.

Using the RHESSI data, Watts & Strohmayer (2006) were able to confirm the RXTE detection of the 92 Hz QPO. We also found QPOs at 18 Hz and 26 Hz, at the same rotational phase as the 92 Hz QPO. A weak feature at 30 Hz was not significant at the  $3\sigma$  level once number of trials were taken into account, so we were not able to make an independent confirmation of this result (but see below). The most exciting discovery, however, was at higher frequencies. Using photons with nominal energies in the range 100–200 keV (higher than the RXTE PCA energy band), we found a QPO at 625 Hz. The QPO seemed to emerge earlier in the tail than the 92 Hz QPO, and was strongest at a different rotational phase. A signal at 625 Hz was particularly exciting as it is very close to the frequency predicted for the  $n = 1$  overtones of the torsional shear modes (Piro, 2005).

Once the RXTE data of the SGR 1806-20 giant flare went public we re-analysed this dataset to check the RHESSI results and perform a thorough rotational phase dependent search for additional QPOs (Strohmayer & Watts, 2006). We were able to confirm the RHESSI detections of the 18 and 26 Hz QPOs, and their rotational phase dependence. We were also able to confirm the presence of the 30 Hz QPO found by Israel et al. (2005) and showed that it too is rotational phase dependent. A comparison of the spectra of photons

detected by RHESSI and RXTE indicated why the 30 Hz feature was weaker in the RHESSI data: the feature is strongest at low energies, a range in which RHESSI is very noisy due (most likely) to scattering.

Rotational phase dependent analysis also revealed new surprises in the RXTE data. The first was a QPO at 150 Hz, very close to one of the frequencies detected in the SGR 1900+14 flare. There was also an additional QPO at 1840 Hz, close to the frequency expected for the  $n = 3$  overtone of the torsional shear modes. Most exciting, however, was a QPO at 625 Hz, the frequency identified in the RHESSI dataset. Compared to the RHESSI QPO, the RXTE QPO had lower fractional amplitude, lower coherence and a different rotational phase dependence. It also appeared later in the tail of the flare, and in a lower energy band. In the context of the seismic mode model this suggests two possibilities. The first is that we are seeing evolution of one mode due to changing emission conditions. At early times, the signal emits at high fractional amplitude in an energy band above that of the RXTE PCA, so is only seen in RHESSI. At later times, the amplitude decays but so does photon energy, at which point the signal is too weak to be seen in RHESSI (which recorded a lower count rate since we can only use front segments for high frequency signals) but is detected in the RXTE data. A second possibility is that we are seeing two different  $n = 1$  modes, since the different angular harmonics of the  $n = 1$  modes have very similar frequencies (Piro, 2005).

The 92.5 Hz QPO also showed strong evidence for variability in amplitude and frequency over the course of the tail. Whether this is a property of the underlying oscillation, or indicative of variations in the emission mechanism and stellar environment, is as yet unclear. Without better data it could be hard to pin this down.

## 2.2 *Impulsive phase*

In addition to the variability observed in the tails of giant flares, there is evidence for variability in the earlier, impulsive phase of the flare. Barat et al. (1983), analysing Prognos and Venera data from the first 200ms of the 1979 giant flare (the only high time resolution data available), found evidence for variability at a frequency of  $\approx 43$  Hz. Geotail observations of the first 500ms of the SGR 1806-20 flare indicate periodicity at  $\approx 50$  Hz, but no similar phenomena are seen in the SGR 1900+14 flare (Terasawa et al., 2006).

Analysing variability in the impulsive phase is challenging, as there are complicated dead-time effects. However, the evidence is now mounting for variability in this early phase, preceding the QPOs that appear later in the tail once the surface of the star is visible. Whether the two phenomena are related is an

SGR 1806-20	SGR 1900+14	Torsional shear mode identification
18*		
26*		
30*	28	$n = 0, l = 2$
	53	$n = 0, l = 4$
92*	84	$n = 0, l = 6$
150		$n = 0, l = 10$
	155	$n = 0, l = 11$
625*		$n = 1$
1840		$n = 3$

Table 1

Summary of QPO frequencies (in Hz) detected in the tails of the SGR 1806-20 and SGR 1900+14 giant flares. QPOs with asterisks have been detected in both the RXTE and RHESSI datasets. The 150 Hz and 1840 Hz QPOs in the SGR 1806-20 flare have fractional amplitudes too low to be detected in RHESSI. The third column indicates the identification as torsional shear modes on the basis of models that do not include crust-core coupling. The mode identification that we have given for the  $n = 0$  modes is consistent with that given in Samuelsson & Andersson (2006). This differs very slightly from the identification given in our previous papers and in Piro (2005), and reflects the use of a (more accurate) spherical geometry in the more recent paper.

interesting question. The timescales are similar, and it is possible that we are seeing the event that triggers global vibrations or an earlier manifestation of those oscillations. As in the previous section this question will only be settled with better data.

### 3 Global seismic vibration models

#### 3.1 State of theoretical modelling

The frequencies of the QPOs are in good agreement, for the most part, with models of torsional shear modes of neutron star crusts - in accordance with the early theoretical suggestions. The models used to make these identifications were based on early calculations that assumed free slip of the solid crust over the fluid neutron star core (Hansen & Cioffi, 1980; McDermott, van Horn & Hansen, 1988; Strohmayer, 1991; Strohmayer et al., 1991). The models have since been improved to include the following effects: gravitational redshift; the effec-

tive boost to the shear modulus due to isotropic magnetic pressure (Duncan, 1998); up to date models of crust composition (Haensel & Pichon, 1994; Piro, 2005); General Relativity and elasticity (Samuelsson & Andersson, 2006). Using these free slip models, in which the crust moves independently of the core, one arrives at the mode identifications summarized in Table 3.1. Whilst most of the modes fit the model well, the two lowest frequency modes in the SGR 1806-20 dataset do not fit comfortably.

The models described above have limitations in their treatment of the magnetic field. The assumption of an isotropic magnetic field is clearly inadequate - we know that magnetars have strong dipole field components and are also likely to have strong internal toroidal fields (Braithwaite & Spruit, 2006). The field also couples the crust to the fluid core, modifying the boundary conditions at the interface. A number of papers have started to tackle these issues (Carroll et al., 1986; Messios, Papadopoulos & Stergioulas, 2001; Glampedakis et al., 2006; Lee, 2006; Sotani et al., 2006a,b). Ultimately what one needs to do is to compute global magneto-elastic modes of the star, taking full account of the coupling. An initial attempt to do this for a uniform field, using simple slab geometry, was made by Glampedakis et al. (2006). Slab geometry is often used when computing crust modes, since curvature can be neglected in the thin crust limit. Clearly it has its limitations when computing global modes, as it does not properly treat the conditions in the centre of the star. However, the results from this simple model were extremely interesting. Inclusion of the coupling resulted in a set of modes whose amplitudes were strong in the crust and weak in the core, with frequencies almost identical to the frequencies computed when coupling was neglected. However, the model also generated additional modes with lower frequencies that could explain the 18 and 26 Hz QPOs detected in the SGR 1806-20 flare.

At this point it is appropriate to discuss the paper by Levin (2006) that argued against global seismic vibrations as a viable mechanism for the magnetar QPOs. The first part of the paper points out that if there is strong displacement at the base of the crust then any movement of the crust would necessarily cause Alfvén waves to propagate into the core. This point is perfectly valid - one must, as we pointed out in the previous paragraph, consider crust/core coupling. Levin then moves on to consider the oscillations in the fluid core, using a toy model of a slab of fluid threaded by a position-dependent field. The particular model chosen possesses a continuous spectrum of apparently singular modes. Levin then adds a solid oscillating plate (the ‘crust’) to the top of the slab, and argues that this will couple to the continuous spectrum, causing energy to drain from the oscillating plate on a rapid timescale. On this basis he concludes that coupled oscillations are also not viable as they will die away too rapidly.

The first problem with the toy model employed by Levin is that the contin-

uous spectrum is an artifact of the simple geometry, in particular the fact that the model is unbounded in one dimension (the ‘z’ dimension). The model also neglects the fact that there should be a ‘crust’ on the lower edge of the slab as well. Once the proper boundaries are included one can compute perfectly viable discrete modes: this is demonstrated by the computations in Glampedakis et al. (2006). The varying-field problem, when properly posed, may admittedly still give rise to continuous spectra for certain frequency bands. However, the assertion made by Levin that this automatically leads to rapid energy loss (based on an analogy with a quantum mechanical problem) is certainly not proven. Studies of continuous spectra in differential rotation problems, for example, show that the temporal behaviour of the collective physical perturbation resulting from a continuous spectrum is complicated. Decay of perturbations can be polynomial - much slower than exponential decay - and discrete stable modes can persist perfectly well even in the frequency bands occupied by the continuous spectra (Watts et al., 2003, 2004). Levin’s conclusions about the viability of global seismic modes, based on the model presented in his paper, are not sustainable.

Accurate dissipation timescales for such global modes remain to be calculated in detail. However, estimates by Schumaker & Thorne (1983) and McDermott, van Horn & Hansen (1988) suggest that damping due to gravitational wave emission and neutrino losses should be low. Blaes et al. (1989) estimated damping due to Alfvén wave losses for crust-only modes and found that damping drops off substantially for frequencies below several kHz. This would prolong global mode lifetimes in the frequency range of interest, a point also noted by Duncan (1998). As mode calculations become more sophisticated all of these effects will have to be revisited. Other factors that need to be assessed include dissipation within the core, viscous effects at the base of the crust, and the presence of crustal inhomogeneities. The effect of the unusual magnetospheric conditions also needs to be taken into account, since the presence of the trapped fireball, which has a major impact on emission properties, will also affect energy loss. For the moment, however, the estimates are such that the modes could survive long enough to explain the observations.

The precise nature of behaviour at the crust/core interface also needs more detailed consideration. Boundary layer physics will be crucial (Kinney & Mendell, 2003), as will the elastic properties at the base of the crust (Pethick & Potekhin, 1998). Coupling will also depend rather sensitively on field geometry: the modes that survive may be those for which coupling to the core is minimal. Indeed the modes found by Glampedakis et al. (2006) had very weak amplitudes in the core. The presence of a strong toroidal field in the core would also increase its rigidity, rendering it less prone to excitation. Until all of these issues are addressed, the global seismic vibration model remains the most promising mechanism for explaining the QPOs, particularly given the difficulties faced by the alternative mechanisms, discussed in Section 5.



### 3.2 Neutron star seismology

Assuming that the global seismic vibration model is the correct mechanism underpinning the oscillations, one can start to deduce the properties of the magnetars' interiors. This section summarises some of the early findings.

The frequencies of the fundamental  $n = 0$  torsional shear modes deduced for SGRs 1806-20 and 1900+14 are different, the latter having a lower fundamental. This most probably reflects differences in the mass, radius or magnetic field strength of the two stars (mass and radius having a strong effect due to gravitational redshift). Strohmayer & Watts (2005) analysed the differences in mass and magnetic field that would be necessary to explain the different frequencies, for various different equations of state (Lattimer & Prakash, 2001). Estimates of the magnetic field derived from timing (Woods et al., 2002) constrain the parameter space to rule out both very hard and very soft equations of state. For intermediate equations of state reasonable results were obtained that support the finding that SGR 1806-20 has a stronger field than SGR 1900+14.

The possible identification of an  $n = 1$  radial overtone is particularly exciting, as it enables us to estimate crust thickness. This is on its own an independent constraint on the nuclear equation of state. In the Newtonian perturbation calculations of Hansen & Cioffi (1980), one can show that in the thin crust limit the ratio of first radial overtone to fundamental frequency is proportional to the ratio of crust thickness to stellar radius. Subsequent Newtonian perturbation calculations included a correction to the frequency for gravitational redshift; a factor which cancels when one takes the ratio of two frequencies. Strohmayer & Watts (2006) used this fact to compute mode frequencies for realistic (non-thin) neutron star crust models in spherical geometry. Using the SGR 1806-20 observations, assuming a fundamental at 30 Hz and a first overtone at 625 Hz, this resulted in a crust thickness estimate of 0.1–0.13 times the stellar radius. Recent more detailed modelling is now refining this initial value. General relativistic mode calculations by Samuelsson & Andersson (2006) and Sotani et al. (2006a), which take into account not only gravitational redshift but also the effect on crust thickness associated with relativistic models, have already resulted in revised estimates. Efforts to include crust/core coupling will doubtless lead to further changes (Glampedakis et al., 2006; Sotani et al., 2006b). This is nonetheless the first time that there has been the possibility of making a direct measurement of crust thickness in a neutron star.

This is particularly important for strange star models. Strange stars are hypothetical compact objects, proposed by Witten (1984), composed entirely of stable strange quark matter. Their predicted properties are very similar to those of neutron stars. However, models predict that their crusts should differ,

the major difference being that they are much thinner than neutron star crusts (Alcock et al., 1986; Jaikumar et al., 2006). Watts & Reddy (2006) have recently computed torsional shear mode frequencies for strange star crust models to see whether they are compatible with the observations. The frequencies found differ substantially from the frequencies found for neutron star crusts, and there is a particular problem with the overtone frequencies. As expected, the thin crust, coupled with effects due to the strong field, pushes the frequencies of the overtones up. Even given very poor constraints on some of the strange matter parameters, the overtone frequencies are far too high to explain a QPO at 625 Hz. These findings need to be verified using more sophisticated models, but this may well be a robust method to rule out strange stars.

## 4 Gravitational wave searches

Non-axisymmetric oscillations of neutron stars will emit gravitational radiation. Magnetar starquakes are therefore of interest as potential sources for detectors such as the *Laser Interferometer Gravitational-Wave Observatory* (LIGO). Estimates of the gravitational wave emission of crustal torsional shear vibrations indicate that the signals would be far too weak to be detected even by Advanced LIGO (Schumaker & Thorne, 1983). However, if the oscillations also involve the core, prospects for detection improve. At the time of the 2004 giant flare from SGR 1806-20, only the 2km interferometer at LIGO's Hanford site was taking data. LIGO scientists are at present analysing this data to place upper limits on any periodic gravitational wave signal at the detected frequencies. Details of the analysis were presented by Matone (2006), and upper limits should be forthcoming in the near future. Since the 2004 event, the sensitivity of LIGO has improved still further, and (particularly with the 4km detectors operating) prospects for setting even more stringent upper limits on future events are good.

## 5 Alternatives to seismic models

### 5.1 Modes of a debris disk

In a recent paper, Wang et al. (2006) reported the discovery of a debris disk around a magnetar, the Anomalous X-ray Pulsar 4U 0142+61. Many neutron stars in binary systems exhibit high frequency QPOs that are thought to originate in the accretion disk (van der Klis, 2006). It has therefore been suggested that a similar phenomenon might be responsible for the magnetar QPOs.

It is important to note that there is no evidence as yet for fallback/debris disks around SGRs, although giant flares clearly expel plasma. There is also no evidence from the kHz QPOs of normal neutron stars for the sequence of frequencies that we find in the SGRs, or for any rotational phase dependence. However, most importantly there are major differences between the accretion disks in neutron star binaries and the debris disk found by Wang et al. (2006). The critical property for timing purposes is the inner disk radius. For the neutron stars that show high frequency QPOs the inner disk radius is close the neutron star, and the orbital frequencies in the disk can exceed 1000 Hz. All current kHz QPO models rely on the presence of rapid orbital frequencies within the disk (van der Klis, 2006). The inner disk radius for the debris disk around the magnetar is, by comparison, several solar radii. There are no rapid orbital frequencies in this system. This alone seems to rule out disk models as a viable mechanism for the magnetar QPOs.

## 5.2 *Modes of the magnetosphere*

Vibrations within the magnetosphere have been suggested by several authors as a possible alternative to global seismic vibrations of the star. A simple estimate of Alfvén speeds in the magnetosphere suggest that the frequencies of global Alfvén modes would be too high. However, there may be alternative magnetospheric mechanisms. A recent paper by Beloborodov & Thompson (2006) on magnetar coronae indicates that there should be very high frequency quasi-periodic oscillations ( $\sim 10$  kHz) in the inner coronal electric current due to the corona being in a state of self-organized criticality. Lower frequency oscillations would require larger lengthscales and so would probably have to involve the outer corona: but emission is much weaker in this region, making it difficult to achieve the measured QPO amplitudes. However, further work on the state of the corona in the immediate aftermath of a giant flare is required before a coronal mechanism can be ruled out conclusively.

## 6 Conclusions

Neutron stars are the best laboratories for extreme physics in the Universe. Understanding the nature of matter in the cores of neutron stars would be an immense step forward in nuclear physics, and the magnetar QPO detections represent the first serious opportunity to study this region using seismology. Early analysis has already shown the immense potential of this technique to constrain the nuclear equation of state and crust thickness of neutron stars, findings that may rule out strange star models. Whilst there are many theoretical issues still to be resolved, the most urgent requirement is to improve our

observational capability so as to obtain the best possible data of any future giant flare. The potential scientific payoff easily justifies the effort.

## 7 Acknowledgments

We are grateful to Luca Matone for discussions about the gravitational wave search, Andrei Beloborodov for his thoughts on magnetospheric oscillation mechanisms, and Deepto Chakrabarty for pointing out that a large inner disk radius would preclude a disk as a mechanism for the QPOs. ALW is also grateful to COSPAR for a travel grant that enabled her to attend the Beijing meeting.

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